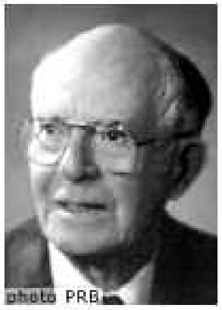
The Nobel Prize in Physics 2002

微中子天文學

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

X射線天文學

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"



Raymond Davis Jr.

1/4 of the prize

USA

University of Pennsylvania
Philadelphia, PA, USA

b. 1914

Masatoshi Koshiba

1/4 of the prize

Japan

University of Tokyo
Tokyo, Japan

b. 1926

小柴昌俊, 東京大學

Riccardo Giacconi

1/2 of the prize

USA

Associated Universities Inc.
Washington DC, USA

b. 1931
(in Genoa, Italy)

2002年諾貝爾物理獎(1/2)

「微中子天文學」

- Raymond Davis與Masatoshi Koshiba (小柴昌俊)之工作

報告人：蘇漢宗 (成大物理系 天文實驗室)

Beta decay

- Beta decay (1920s)

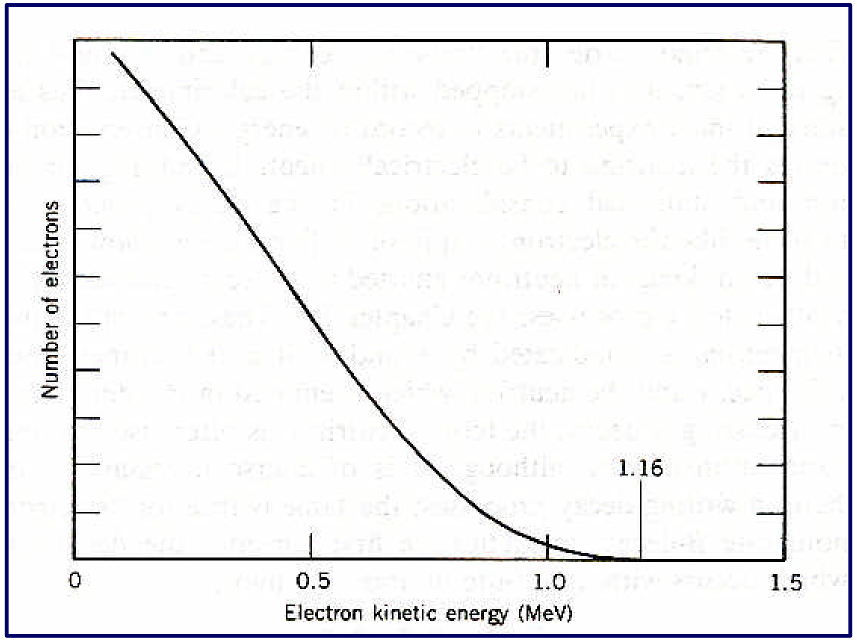
$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X' + e^{-} \quad (n \rightarrow p + e^{-}) $$

- The puzzle (**二體問題，反應能** = Q)

$$ K_e = \frac{m_{X'}}{m_e + m_{X'}} Q $$

⇒應具有單一能量！

Energy spectrum for β decay of ^{210}Bi

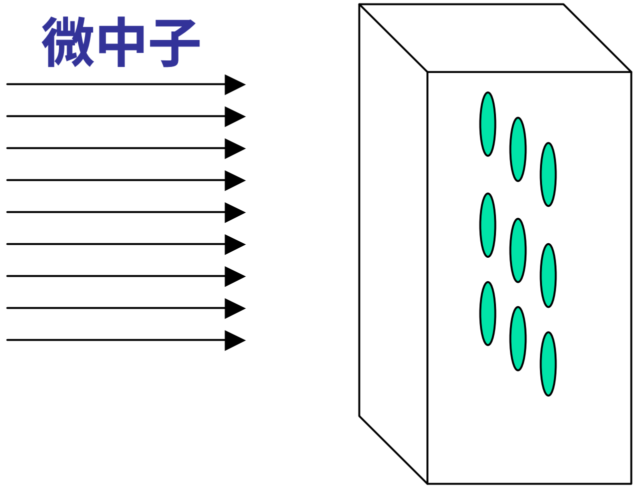


Neutrino (微中子，中微子)

- Proposed by Pauli (1931) ; Named by Fermi

$$n \rightarrow p + e^{-} + \bar{n}_{e}$$

具有中性及高穿透力的特性



- Confirmed (Reines & Cowan, 1956)
  – more than 25 years later!

$$\bar{n}_{e} + p \rightarrow n + e^{+}$$

$$n_{e} + n \rightarrow p + e^{-}$$

$$s_{absorb} = 1.2 \times 10^{-43} cm^{2}$$

1 cm^3 material contains 10^{24} protons

⇒ Absorption probability ~ 10^{-19} cm^{-1}
⇒ Needs 10 light-year of material to capture one neutrino

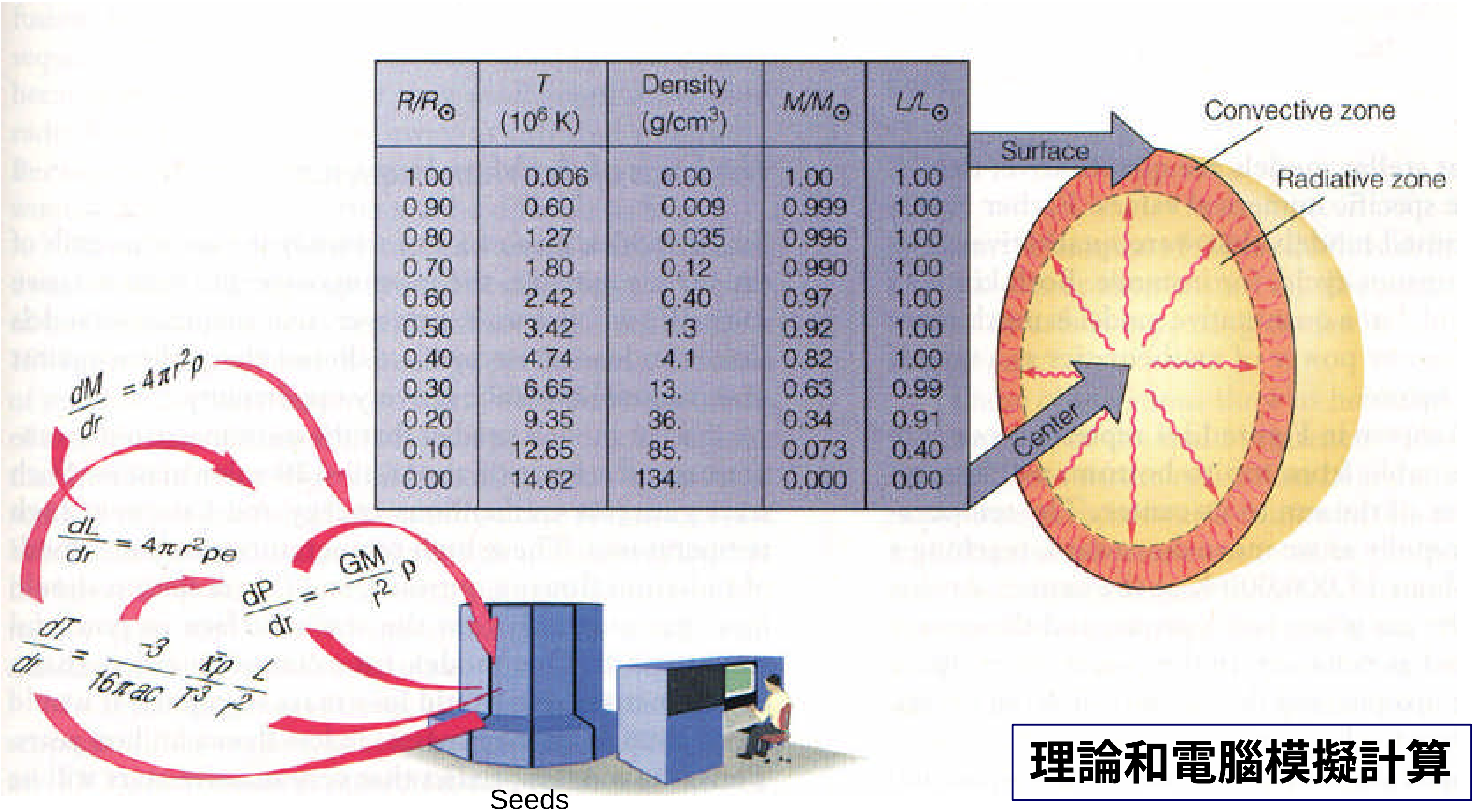
Three-flavor of neutrinos
三種微中子

- Discovery of ν_μ (1962)
- Discovery of ν_τ (1978)
- Three types/flavors of neutrinos

Neutrino	n_e	n_m	n_t
Charged Partner	electron (e)	muon (μ)	tau (τ)

- Bethe (1938, 1939) : a complete theory of nuclear fusion in stars
- Major source of neutrinos on Earth (theory) $\Rightarrow$ Sun

如何得知太陽內部結構為何？



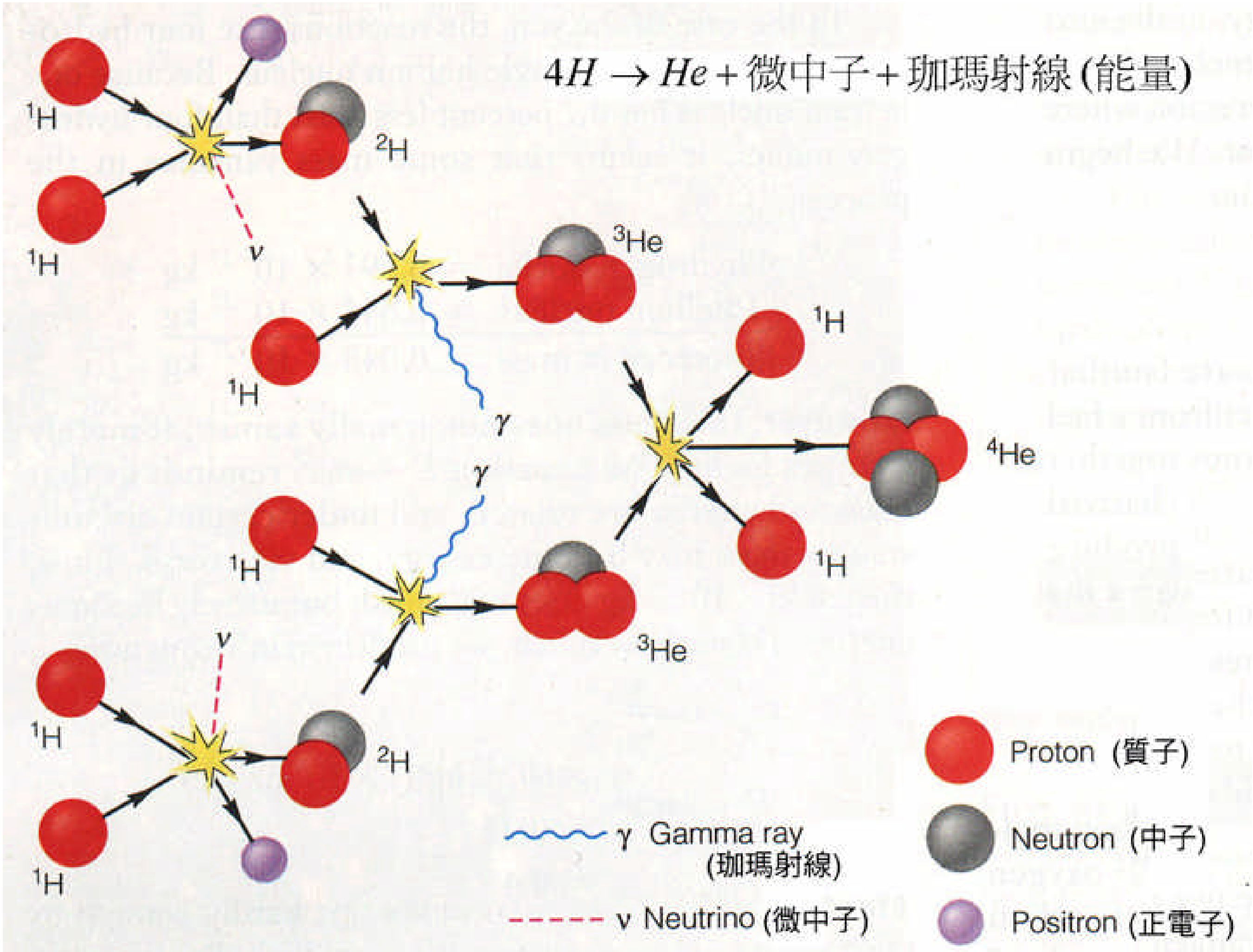
$R/R_\odot$	T (10^6 K)	Density (g/cm^3)	$M/M_\odot$	$L/L_\odot$
1.00	0.006	0.00	1.00	1.00
0.90	0.60	0.009	0.999	1.00
0.80	1.27	0.035	0.996	1.00
0.70	1.80	0.12	0.990	1.00
0.60	2.42	0.40	0.97	1.00
0.50	3.42	1.3	0.92	1.00
0.40	4.74	4.1	0.82	1.00
0.30	6.65	13.	0.63	0.99
0.20	9.35	36.	0.34	0.91
0.10	12.65	85.	0.073	0.40
0.00	14.62	134.	0.000	0.00

Seeds

理論和電腦模擬計算

太陽核心的核融合 (理論)

proton-proton chain



$$n_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^- \quad (threshold = 0.81\,MeV)$$

Pontecorvo & Alvarez (1946, 1949)

太陽核心的微中子工廠 (理論)

- **pp:** $p + p \rightarrow d + e^{+} + n_e \; (0.42\ MeV;\ \mathrm{max})$

- **pep (1/230 of pp):** $p + e^{-} + p \rightarrow d + n_e \; (1.44\ MeV)$

$$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p \quad (85\%)\,; \qquad {}^{3}He + {}^{4}He \rightarrow {}^{7}Be + g \quad (15\%)$$

- **^{7}Be:** $^{7}Be + e^{-} \rightarrow {}^{7}Li + n_e \; (0.86\ MeV - 90\%;\ 0.38\ MeV - 10\%)$

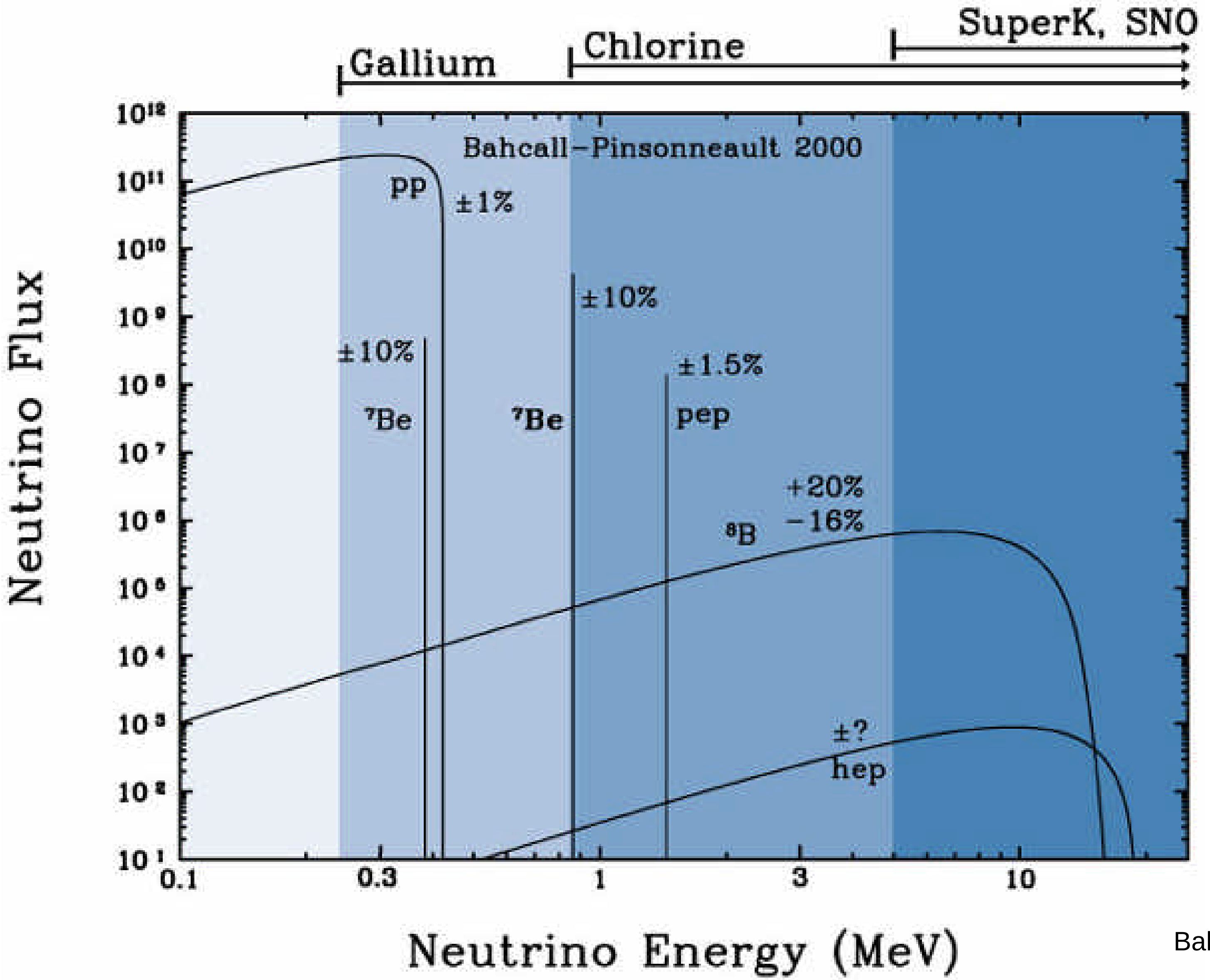
$$^{7}Be + p \rightarrow {}^{8}B + g$$

- **^{8}B** (0.02%)**:** $^{8}B \rightarrow {}^{8}Be + n_e \; (14.06\ MeV;\ \mathrm{max})$

- **hep** (0.00002%) **:** $^{3}He + p \rightarrow {}^{4}He + e^{+} + n_e \; (18.77\ MeV;\ \mathrm{max})$

Neutrino flux from the sun is $10^{10}\ cm^{-2}s^{-1}$

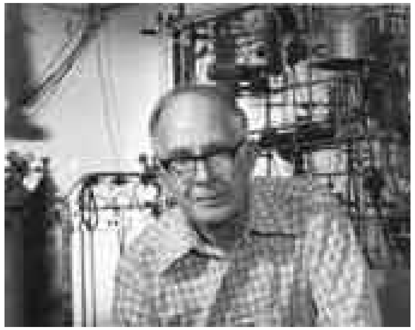
Solar neutrino energy spectrum
太陽的微中子能譜 (理論)



Bahcall

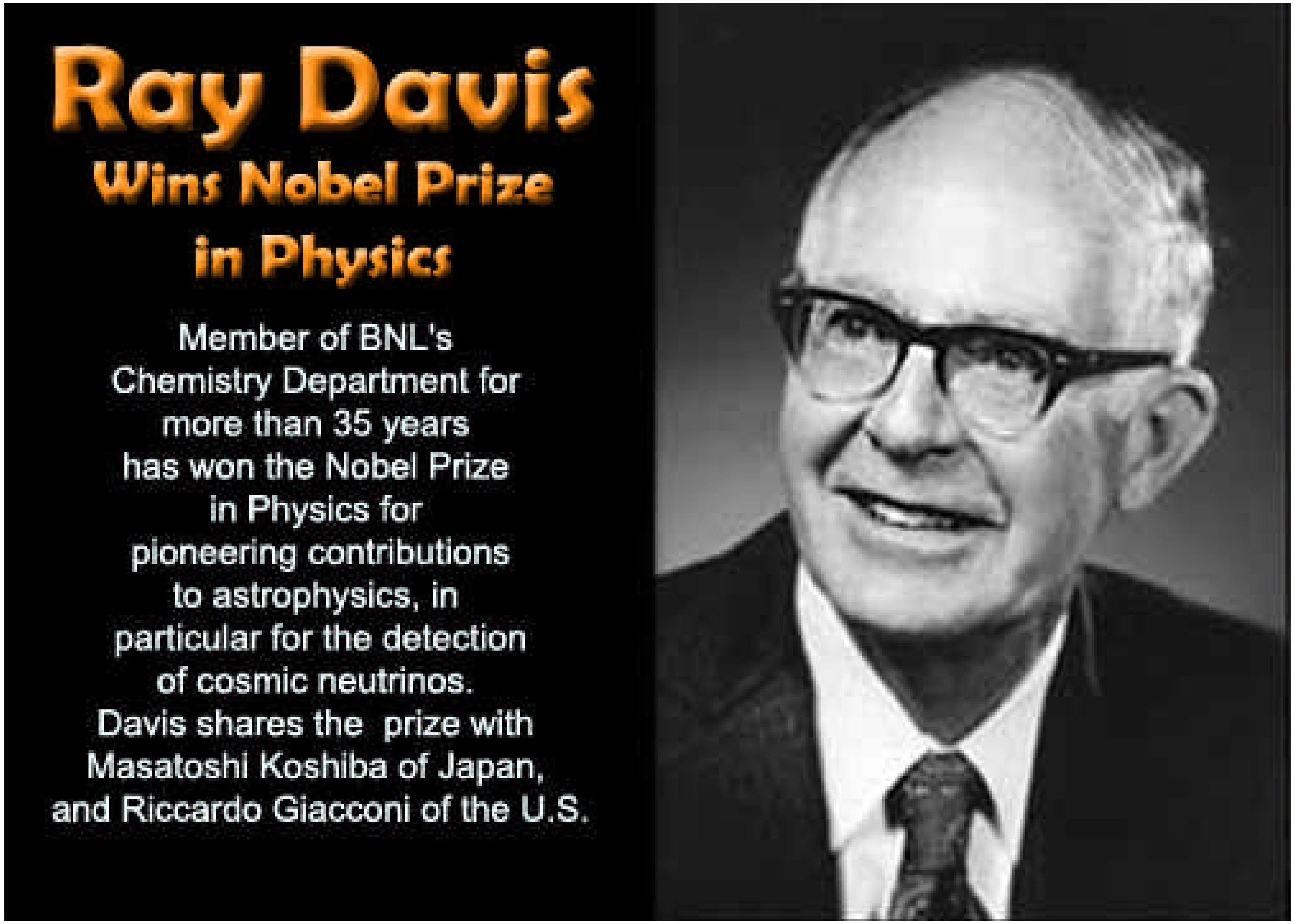
Raymond Davis, Jr (1914-)

1969



1978

1999

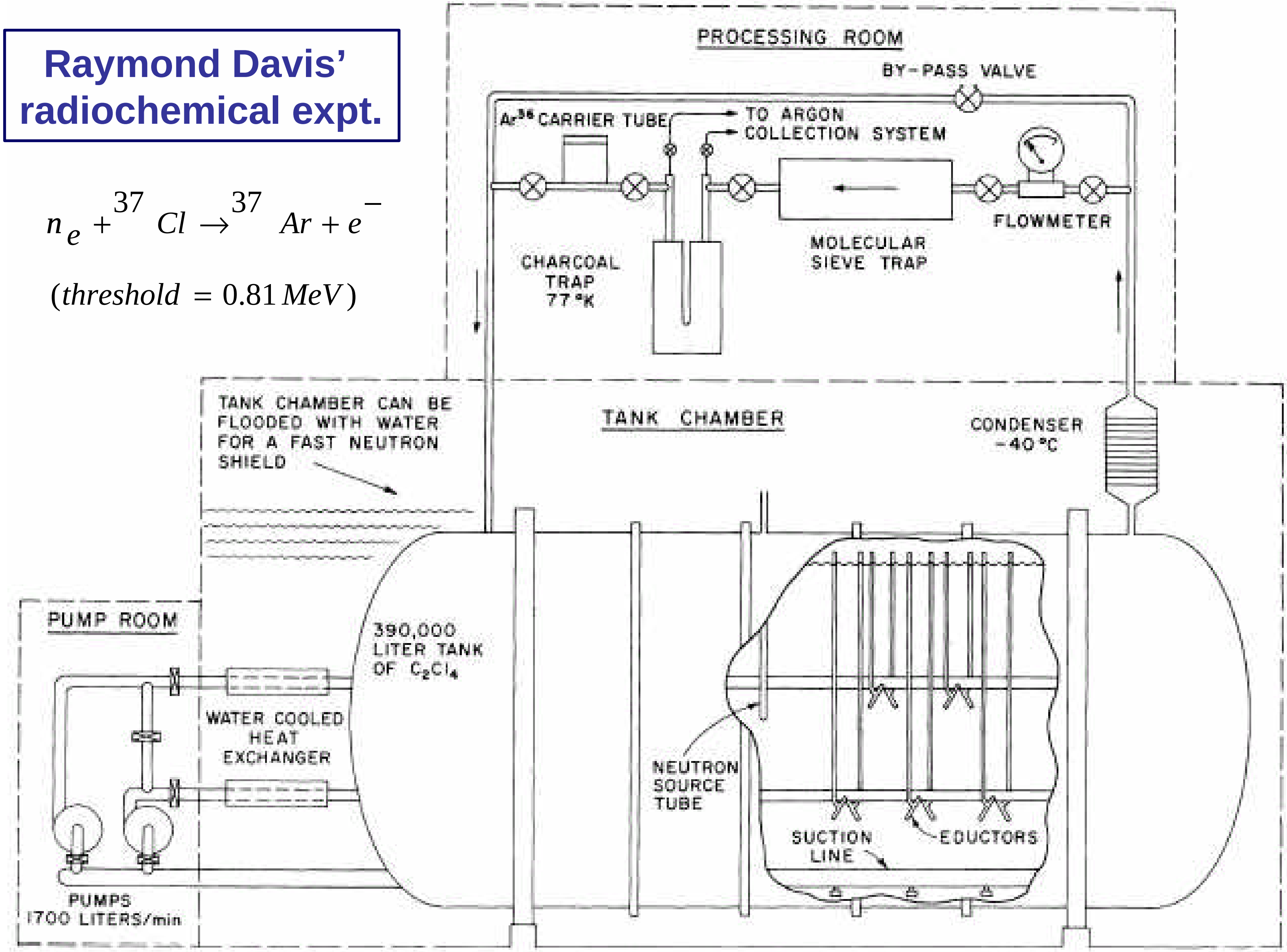


1914~

Raymond Davis' radiochemical expt.

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

$$(threshold = 0.81\, MeV)$$



Homestake solar neutrino experiment

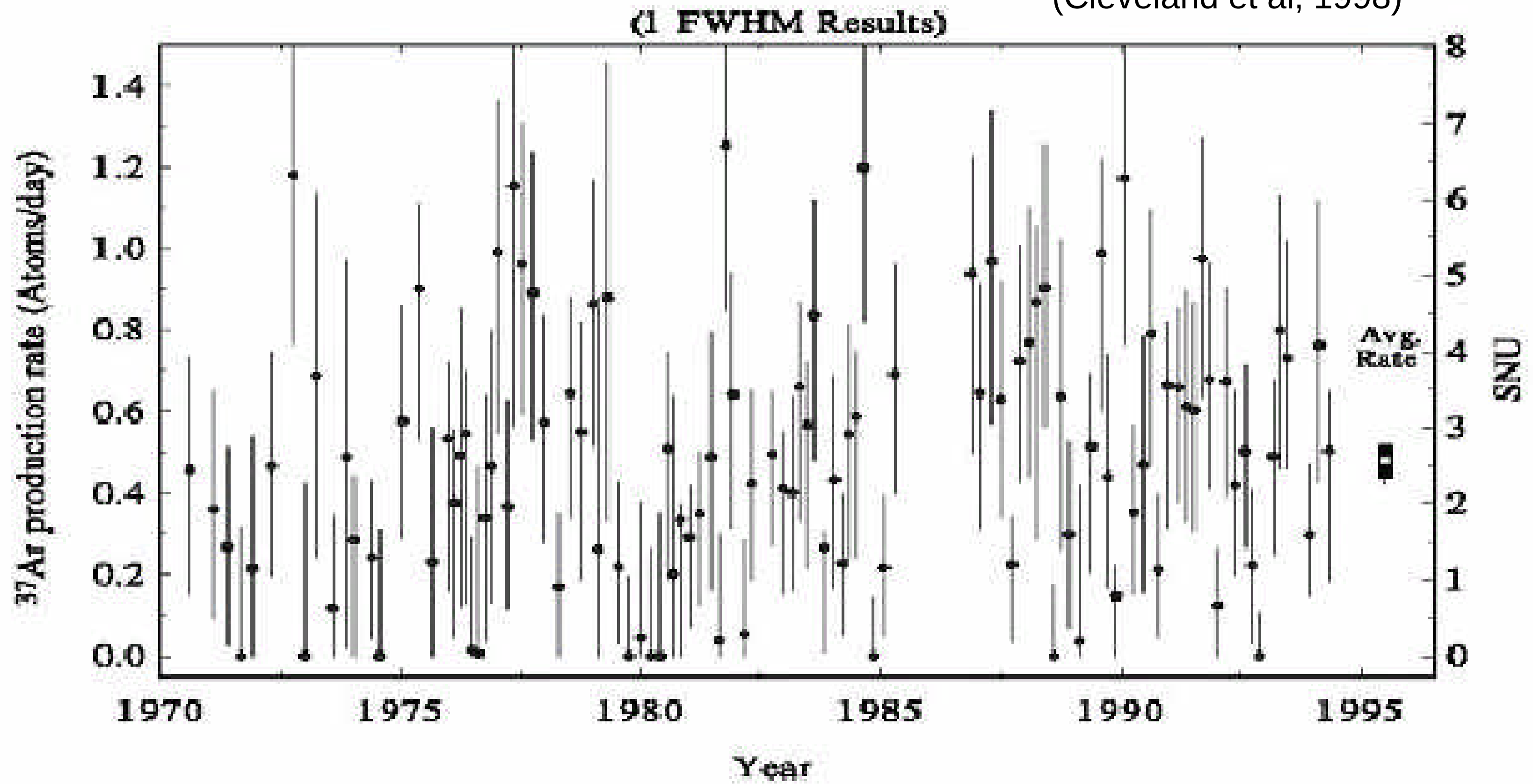
1.5 km underground

- Period: 1970-1994
- 2 x 10^{30} Cl
- ~2200 neutrinos captured, 91% extracted (1997 ^{37}Ar)
- Data rate ~17 ^{37}Ar/2-month
- Solar neutrinos (yes!) (Davis et al. PRL **20**, pp1205, 1968)
- Solar neutrino problem!

The detection rate was 1/3 of the theory predicted!

Homestake's experimental result

(Cleveland et al, 1998)

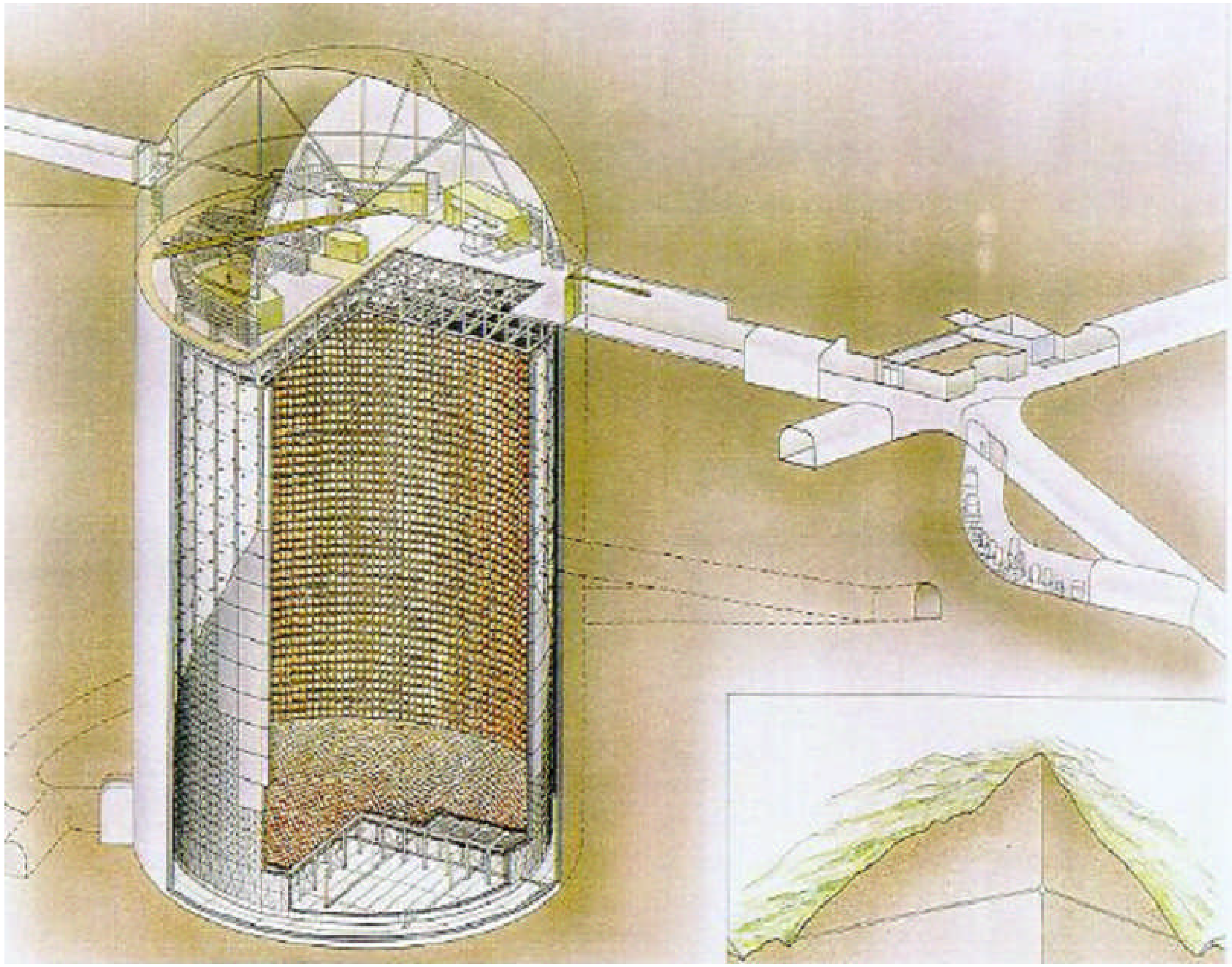


Final results of Davis' experiment. The average rate of about 2.5 SNU is much lower than the calculated rate of about 8.6. (1 SNU = 1 Solar Neutrino Unit, 1 captured neutrino per second and per 10^{36} target atoms)

小柴昌俊 (Masatoshi Koshiba, 1926~)

Designer of the Kamioka and Super-K

- Water: 2.14 x 10^6 litters
- 1100 X 50cm(D) PMTs
- Cerenkov radiation detectors (aka optical sonic boom)
- With real-time and directional finding capability
- Originally for proton decays with threshold of 30 MeV
- Water purified and detectors upgrade in 1984-1986 to detect > 7.5 MeV events (^{8}B only)

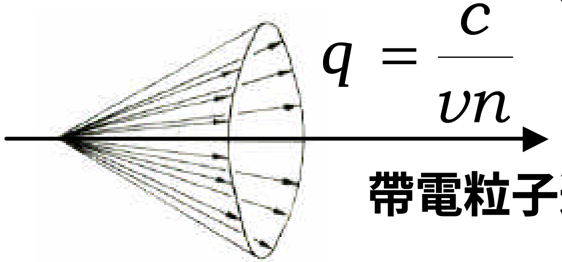


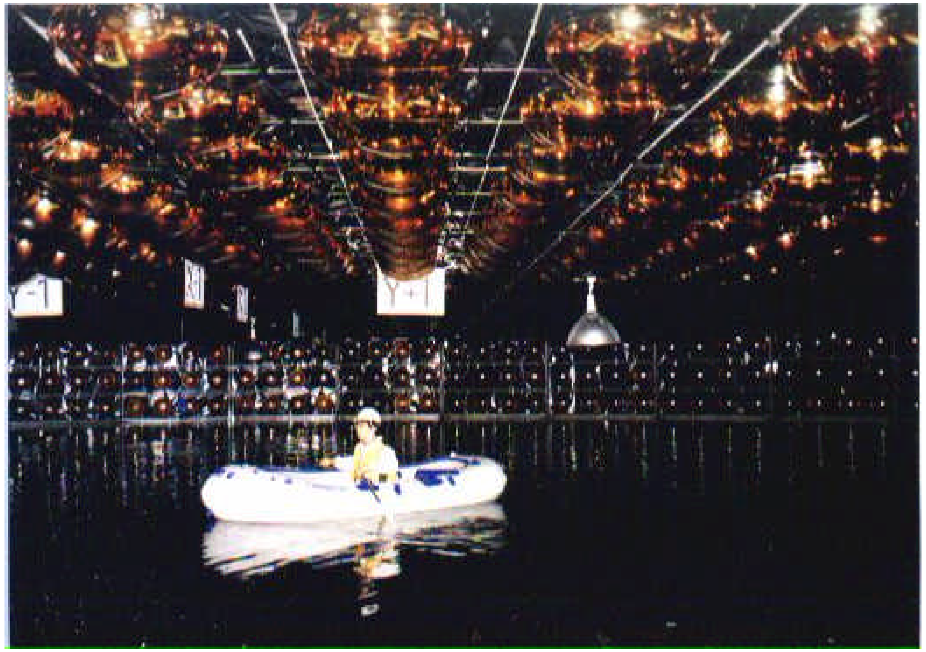
Kamiokande and Super-Kamiokande

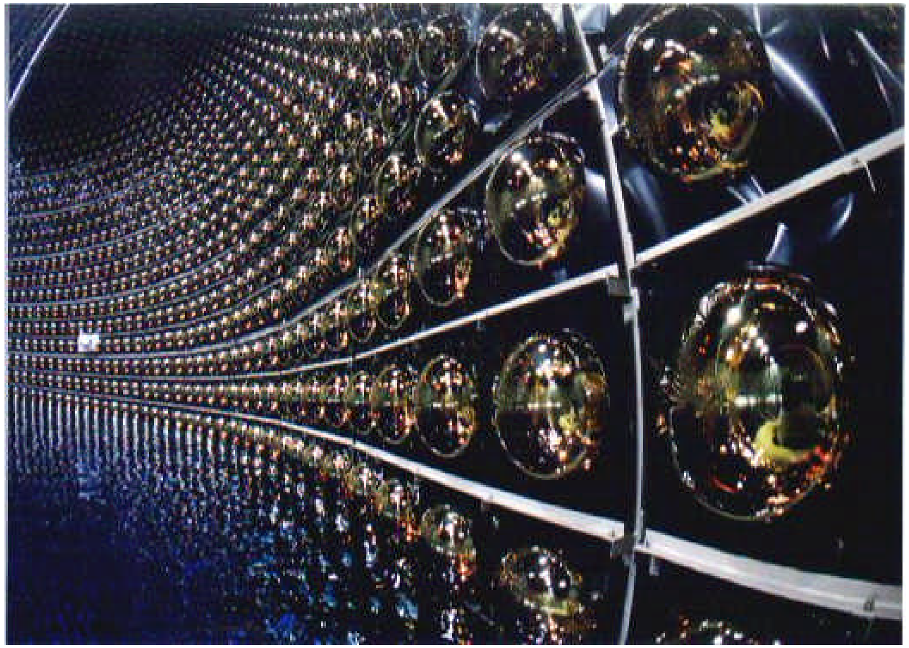
Rafting for solar neutrinos

- Cerenkov radiation (1934, 1958)

$$q = \frac{c}{vn}$$

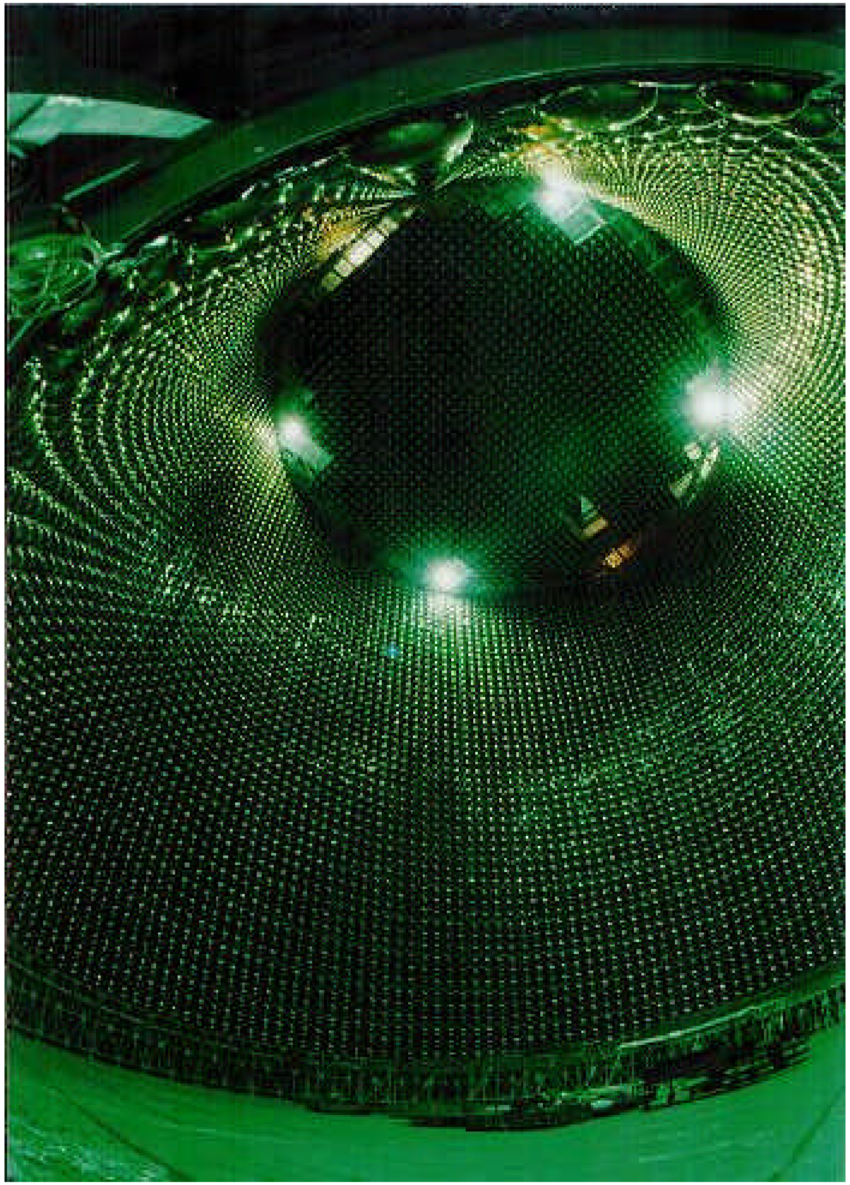






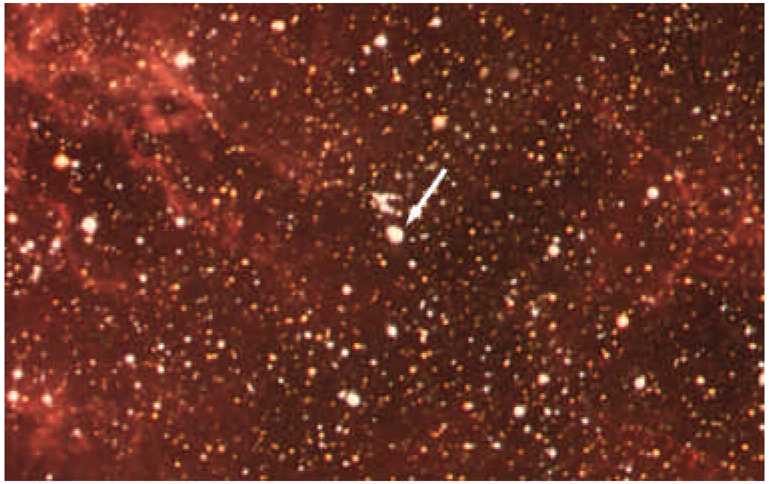
Results of Super-Kamioka

- $\nu_e + e^- \rightarrow \nu_e + e^-$ (solar ν_e)
- $\bar{\nu}_e + p \rightarrow n + e^+$ (hi-E ν_e)
- confirmed the existence of solar neutrinos
- Confirmed the solar neutrino problem (less than 50% theoretical)
- Detected 12 neutrinos from SN 1987A (another 8 events was recorded by IMB detector) (Hirata et al., PRL **58**, pp1490, 1987)

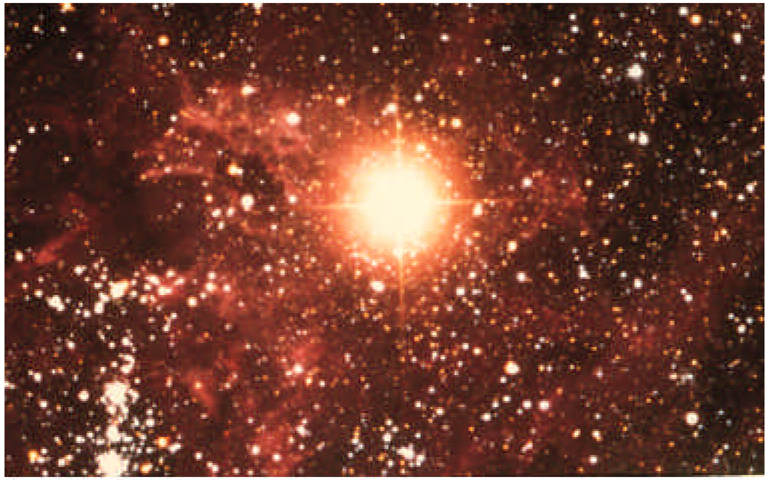


SN 1987A
發現：1987年02月24日

- **可見光發現**：1987**年**02**月**23**日**10:35 UT
- **來源**：LMC
  - **距離** – 170,000**光年** (Tarantula nebula, LMC)
  - **前導星** – Sanduleak –69 202 (**藍超巨星**)
  - $M_{pregen} \approx 20\ M_{sun}$
- SN 1604**以後第一顆目視超新星**
- **用所有現代天文儀器觀測研究的第一顆超新星**



a.



b.

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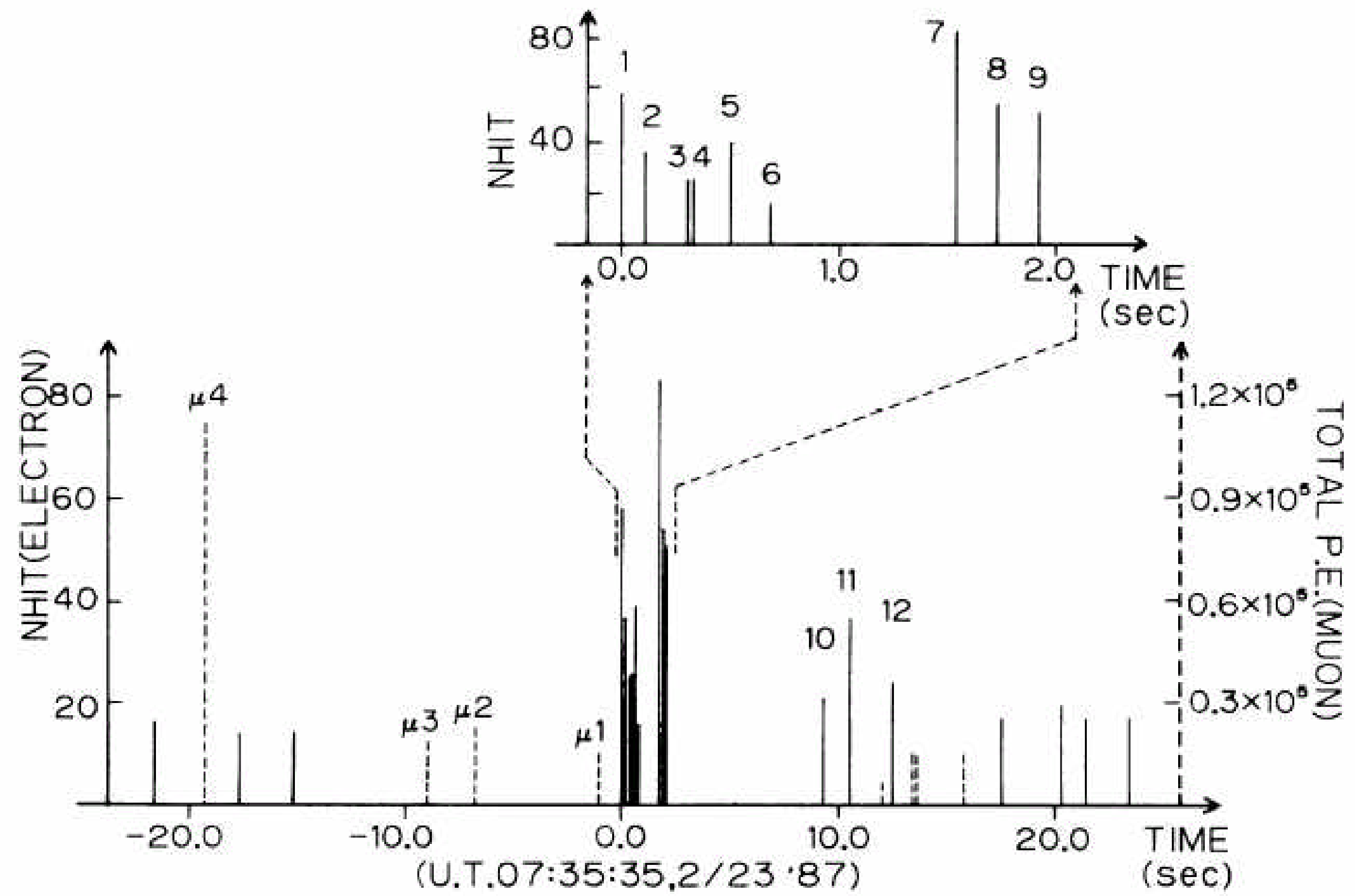
Detection of neutrinos from SN 1987A



- First two events pointed back to LMC ; average neutrino energy is ~ 12 MeV
- Energy that carried away by neutrinos exceeds sun energy output in 10^{10} yrs
- Confirmed the prediction of stellar evolution theory
- Deduced upper mass limit of the electron neutrino is 17 eV

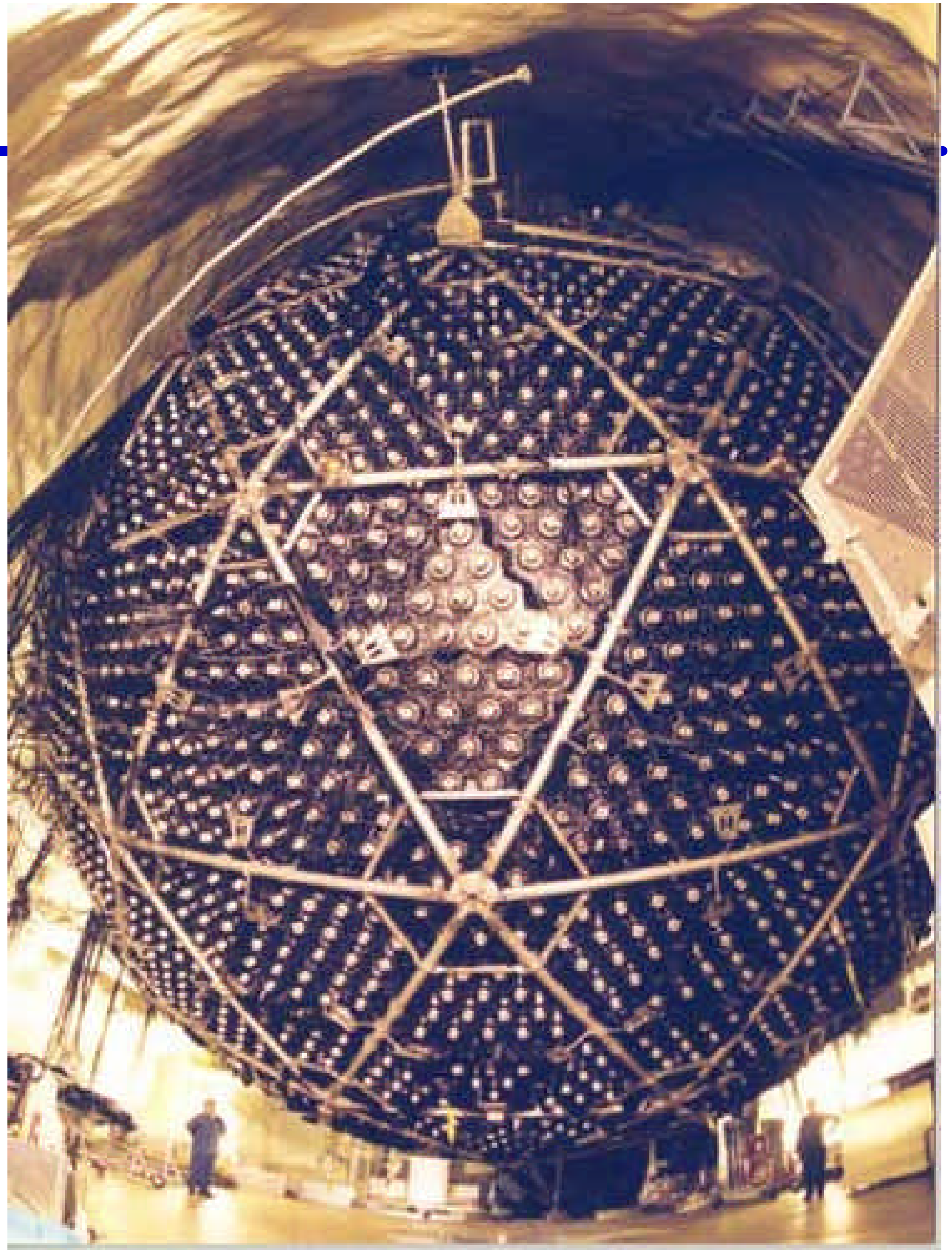
Sudbury Neutrino Observatory

- 2km underground
- surrounded by 9600 PMTs
- 10 x 10^6 litters of ^2H_2O
- two detection modes:

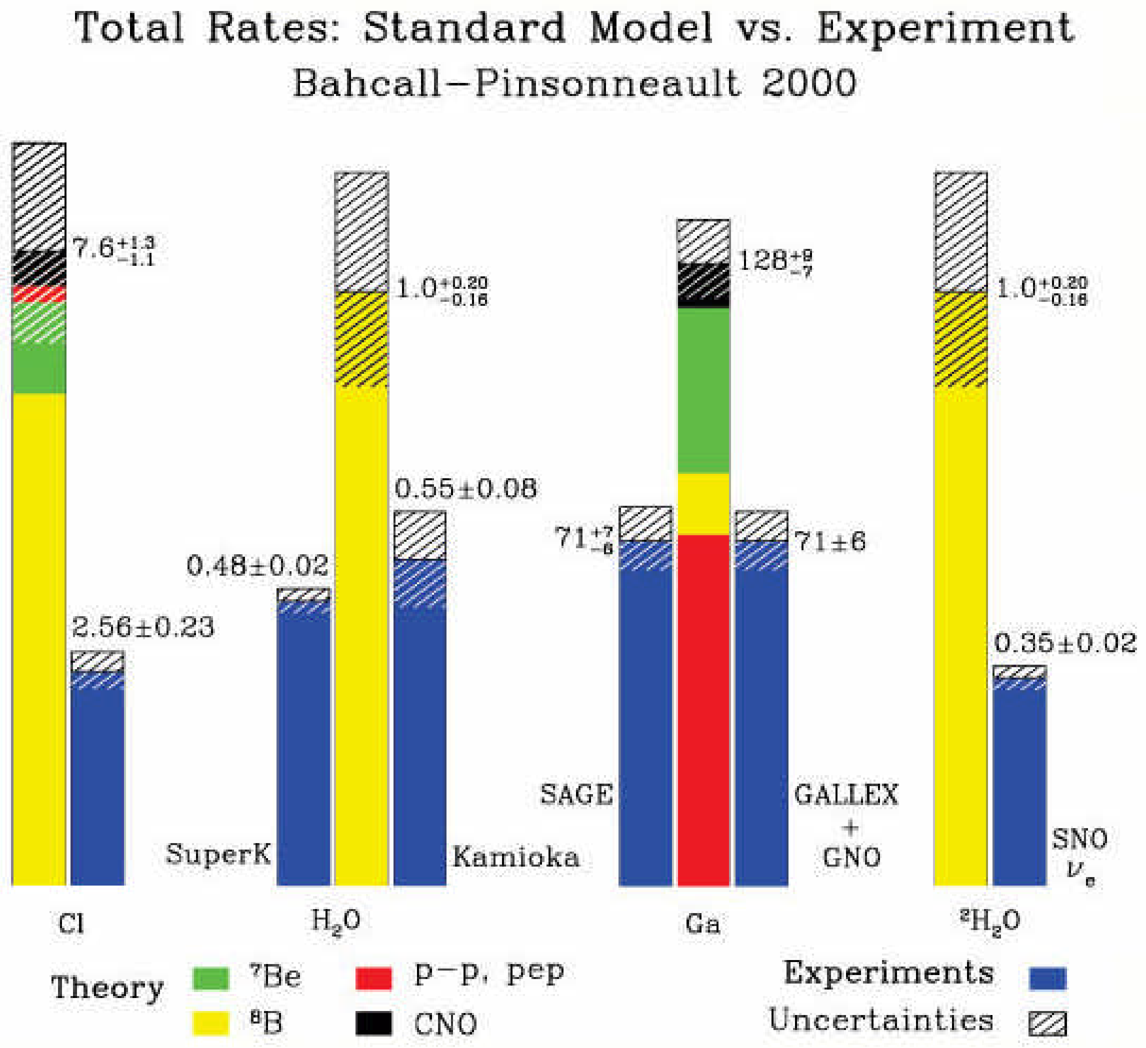
$\nu_e + e^- \rightarrow \nu_e + e^-$

$\nu + d \rightarrow n + p + \nu$

(any neutrinos)



Four solar neutrino problems!



These expts are only sensitive to ν_e (absorption and elastic scattering).

What could be wrong with solar neutrinos?

- Are the experiments wrong?
- Is the solar standard model wrong?
- Are the neutrinos oscillating?

3-flavor of neutrinos $\begin{Bmatrix} n_e \\ n_m \\ n_t \end{Bmatrix}$

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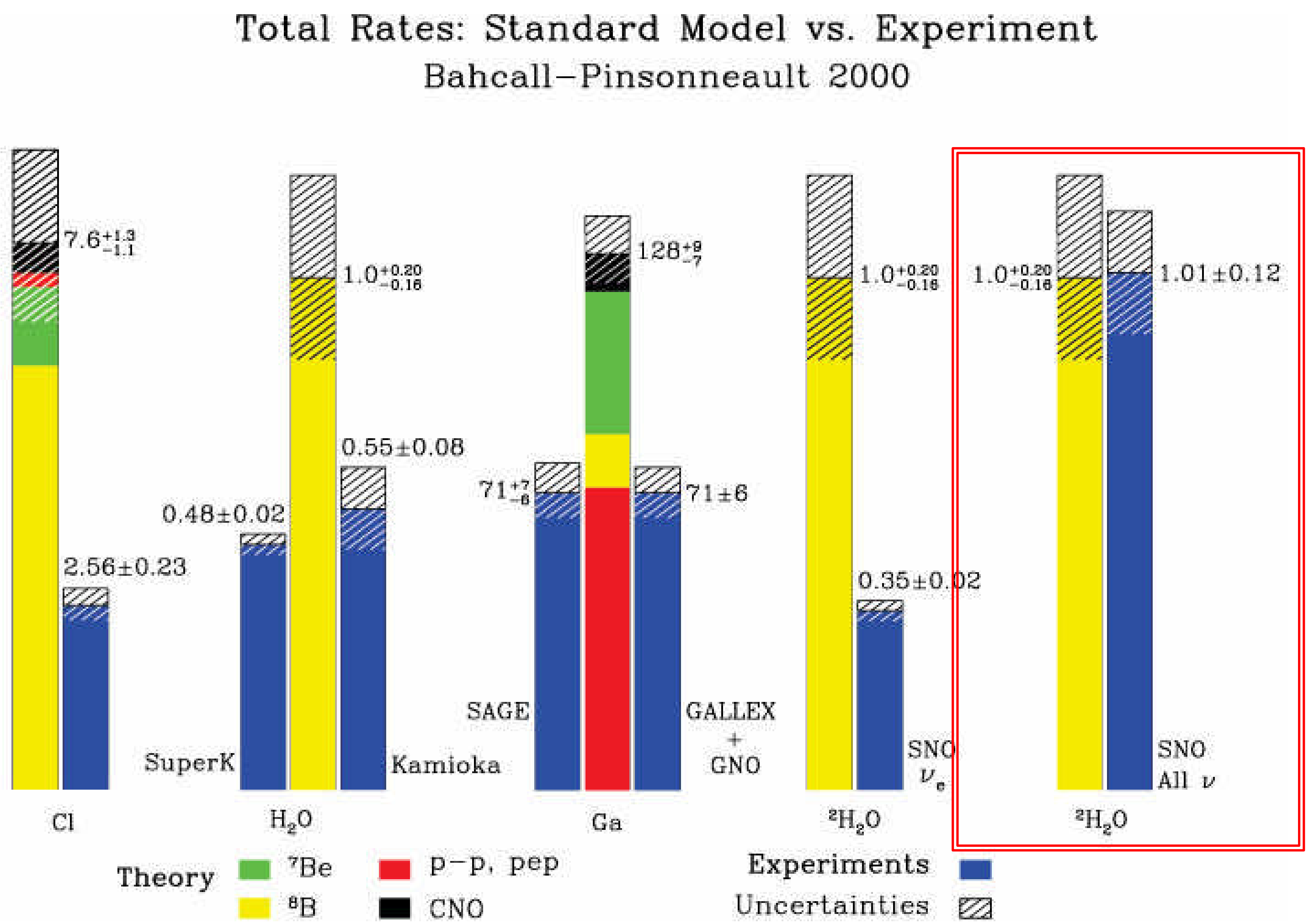
The possible final answer



⇒ The neutrinos probably have tiny masses, and they are oscillating!